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Assessment of radiological hazard of quarry products from southwest Nigeria

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ABSTRACT

The term "quarry products" comprises different natural rocks with different mineral contents, crushed into various sizes at quarries. The concentrations of the naturally occurring radionuclides ^{40}K, ^{238}U and ^{232}Th in quarry products from southwest Nigeria have been measured using gamma ray spectrometry. The gamma absorbed dose rate (D_R), radium equivalent activity (Ra_{eq}), annual effective dose (A_d), activity concentration index (I), external radiation index (H_{ex}) and internal radiation hazard index (H_{in}) associated with the radionuclides are evaluated in order to assess the radiation hazard of quarry products used as building materials. The results showed that a few of the calculated radiological parameters are higher than permissible limit, hence, may pose a radiological hazard when used as building materials.

All the radiological variables above were subjected to correlation analysis to determine the similarities and correlations among various samples. The data sets consist of 10 measured variables. The principal component Analysis (PCA) yields a two component representation of the acquired data, in which 93.3% of the total variance is explained.

1. Introduction

The natural radioelements uranium, thorium and potassium are lithophile elements widely distributed in crustal rocks being concentrated preferentially in acid igneous rocks compared with intermediate, basic and ultra-basic varieties (Alnour et al., 2012; Moura, Artur, Bonotto, Guedes, & Martinelli, 2011). Potassium is a major element widely distributed in crustal rocks, for instance, calcium rich granites may contain up to 2.5% of potassium (Cox, 1991). Thorium occurs predominantly as a tetravalent cation and as a trace constituent in phosphates, simple and multiple oxides and silicates, as well in the major rock-forming minerals such as monazite, thorianite (ThO_2) and thorite ($ThSiO_4$) among others. While Uranium is found in rocks of different mineral species (like apatite, sphene and zircon) as a secondary/accessory mineral or it can form its own minerals. Uranium distribution in rocks is linked to isomorphous mineral substitution, adsorption or inclusion process (Pertlik, Roger, & Adams, 1974). Biotite ("black mica") contains between 19% and 22% of the total uranium because it may contain inclusions of minerals rich in this element, such as zircon. Heavy minerals

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such as zircon, monazite, apatite, magnetite, ilmenite and riebeckite, contain between 61% and 65% of the uranium in a rock (Brown & Silver, 1955; Gabelman, 1977; Gascoyne, M., 1992; Larsen & Phair, 1954; Moreira-Nordemann, 1977; Speeer, Solberg, & Becker, 1981; Tieh & Ledger, 1981).

The presence of naturally occurring radionuclides in construction materials originating from quarry products offers radiation exposure both inside and outside the building environments. This is mainly due to gamma radiation of ^{40}K and members of the uranium and thorium decay series. The term "quarry products" comprises a wide number of different natural rocks with different mineral contents, crushed into various sizes at quarries. This include different geological materials such as gneiss, granite, diorite, granodiorite and other rocks that after an industrial process are suitable for use as building material and ornamental rocks (Ministry of Energy, British Columbia 2014).

Granodiorite is an intermediate coloured, medium to coarse-grained intrusive rock. It falls between granite and quartz diorite, containing more dark minerals than granite but less than quartz diorite. Granite is a pink or greyish coloured rock and represents the lightest coloured variety of intrusive rock. It is medium to coarse-grained and evenly granular. The grains are mainly white to pink orthoclase feldspar with lesser amounts of white to grey plagioclase feldspar and quartz. Diorite is a medium to dark grey, medium to coarse-grained intrusive rock. Gneiss is a medium to coarse-grained, banded, granular metamorphic rock. Distinct colour bands or streaks are produced by the alternation of layers of light (e.g. quartz and feldspar) and dark-coloured (e.g. biotite and hornblende) minerals. The layers do not split readily and when broken are not smooth. Gneiss may form from diorite, granite, shale, sandstone, schist or other rocks (Ministry of Energy, British Columbia 2014). In view of the attractive appearance of these rocks, there is an increasing trend of the public for their use in flooring and interior decoration of building. The use of building material from quarry products containing enhanced gamma activity of naturally occurring radionuclides can pose a radiological hazard to the occupants of such buildings.

Quarry products have been extensively used in Nigeria as building materials. In general, granites are widely recognized to exhibit high levels of uranium, thorium and potassium due to the characteristics of the genetic magma and associated tectonic environment. The knowledge of the level of natural radioactivity in building material is of great importance to determine the associated radiological hazards to human health, to develop reference data of radiological parameters in building material and to develop standards for the use of these materials. This work aims to contribute to a better understanding of the radioactivity distribution in quarry product from selected quarry sites in southwest Nigeria, using gamma spectrometry.

2. Materials and methods

2.1. Sample collection and preparation

A total of fifty (50) samples were collected from ten (10) different quarry sites (five samples from each site). These sites spread across five states (Ogun, Oyo, Osun, Ondo and Ekiti) in which major quarry activities take place in Southwest Nigeria. The coordinates of these quarry sites are listed in Table 1. Each sample was sealed in a well labelled polythene bags and taken to gamma laboratory at Centre for Energy Research and Development (CERD), Obafemi Awolowo University, Ile-Ife for analysis preparation. Wet samples were air dried at room temperature to constant weight and all dried samples were crushed and grinded with Rocklab ring mill, after which they were sieved with a 2-mm mesh and weighed using the OHAUS Adventure Pro AV264 digital balance. Two hundred grams (200 g) each of the samples was weighed into cylindrical polyvinylchloride containers sealed and kept for 28 days in order to attain secular equilibrium between the parent and the daughter nuclides present.

2.2. Gamma ray spectroscopic technique

The activity concentration of natural radioactivity in the samples were determined using a 7.62 cm × 7.62 cm NaI (Tl) detector employed with adequate lead shielding which reduced the background by a factor of about 95%. Energy calibration was done using Standard sources, of known gamma-ray energies and activities, prepared by the Isotope Products Laboratories, Burbank California, USA. The calibration provided qualitative and quantitative analysis of the radionuclides present in each sample. Counting was done for 25,200 s for each of the sample, the calibrated reference material and an empty container were used to determine the background. Current decay data for nuclides were obtained from literature (Arzu, Marie-Martine, Edgardo, & Valery, 2010, 2011). The activities of various radionuclides were determined in Bq kg^{-1} using the count spectra obtained from each of the samples. The gamma ray photo peaks corresponding to energy of 1120.3 keV (^{214}Bi), 911.21 keV (^{228}Ac) and 1460.82 keV (^{40}K) were considered to determine the activity of ^{238}U, ^{232}Th and ^{40}K. The detection limits of the NaI (Tl) detector system were calculated as 31.57, 5.73 and 0.26 Bq kg^{-1} for ^{40}K, ^{232}Th and ^{238}U respectively for a counting time of 25,200 s.

3. Result and discussion

3.1. Activity concentrations of ^{238}U, ^{232}Th and ^{40}K

The specific activity concentration of ^{232}Th, ^{238}U and ^{40}K in the samples are presented in Table 2. The results showed that

Table 1 – Sample ID and coordinate.

Sample ID	Coordinates
OGA	N7° 23′ 30″, E 3° 39′ 16″
OGB	N7° 25′ 47″, E 3° 45′ 09″
OGC	N7° 14′ 51″, E 3° 29′ 32″
OGD	N7° 40′ 29″, E 5° 05′ 59″
OGE	N7° 15′ 25″, E 3° 31′ 38″
OGF	N7° 15′ 32″, E 3° 32′ 19″
OGG	N7° 19′ 22″, E 3° 37′ 36″
OGH	N7° 16′ 50″, E 3° 50′ 47″
OGI	N7° 12′ 59″, E 3° 48′ 53″
OGJ	N7° 20′ 46″, E 5° 15′ 00″

these radionuclides were present in all the samples. The activity concentrations of ^{40}K in the samples ranged from below detection limit BDL to 2004 ± 12 Bq kg^{-1}. The activity concentrations of ^{232}Th ranged from BDL to 561 ± 38 Bq kg^{-1}. While ^{238}U activity concentrations ranged from 5 ± 0.44 to 71 ± 1 Bq kg^{-1}. These variations reflect both the different magmatic sources and processes superimposed on these rocks. In general, thorium accompanies uranium in the magmatic series (Moura et al., 2011); however, discrepancies have been observed in this behaviour. For instance, thorium activity concentration is higher than that of uranium in all the samples analyzed. This may occur due to (a) high mobility and dispersal of uranium causing its retreat from the crystal lattice of the minerals and (b) more difficult thorium migration, which remains retained in the minerals as a consequence of its greater ionic radius.

The mean activities concentrations of ^{40}K from sites OGB, OGD, OGE, OGF, OGG and OGI were observed to be higher than the world average value of 400 Bq kg^{-1}. ^{232}Th mean activities concentrations from all sites are higher than the world average value of 30 Bq kg^{-1}. While the mean activity concentrations of ^{238}U from sites OGA, OGB, OGD, OGI and OGJ are higher than the world average value of 35 Bq kg^{-1} (UNSCEAR, 2000).

3.2. Absorbed gamma dose rate (D_R) and the associated annual effective dose (A_d)

The absorbed dose rate (D_R) and the associated annual effective dose (A_d) due to gamma ray emission from the main primordial radionuclides in the granites were evaluated using data and formulas provided by United Nations Scientific Committee on Effect of Atomic Radiation (UNSCEAR, 2000) and the European Commission (EC, 1999).

In order to convert the activity concentration to absorbed dose rate in air at 1 m above the ground surface for uniform distribution of naturally occurring radionuclides, dose coefficients of 0.92 nGy h^{-1} per Bq kg^{-1} for ^{238}U, 1.1 nGy h^{-1} per Bq kg^{-1} for ^{232}Th and 0.080 nGy h^{-1} per Bq kg^{-1} for ^{40}K were used.

$$D_R\left(nGyh^{-1}\right) = 0.92 \times C_U + 1.1 \times C_{Th} + 0.08 \times C_K \quad (1)$$

Where C_U is the activity concentration of ^{238}U, C_{Th} is the activity concentration of ^{232}Th, C_K activity concentration of ^{40}K in Bq kg^{-1} and D_R is the dose rate in nGy h^{-1}.

The indoor exposure to gamma rays is mainly determined by the materials of construction, and it is inherently greater than outdoor exposure if earth materials have been used (UNSCEAR, 2000). Hence a factor 0.8 and 0.2 were used for the indoor and outdoor occupancy factors respectively and 0.7 Sv Gy^{-1} was used for the conversion coefficient from absorbed dose in air to effective dose received by adults. The components of the annual effective dose, A_d in unit of mSv y^{-1} are determined as follows:

Outdoor

$$A_d\left(mSvy^{-1}\right) = D_R \times 8766 \times 0.2 \times 0.7 \times 10^{-6} \quad (2a)$$

Indoor

$$A_d\left(mSvy^{-1}\right) = D_R\left(nGyh^{-1}\right) \times 8766(h) \times 0.8 \times 0.7\left(SvGy^{-1}\right) \times 10^{-6} \quad (2b)$$

Total

$$A_{dTotal}\left(mSvy^{-1}\right) = A_{dindoor} + A_{doutdoor} \quad (3)$$

The estimated results for absorbed dose rate (D_R) and the associated annual effective dose (A_d) are presented in columns eight to eleven of Table 2. The estimated value for absorbed dose rate (D_R) ranged from 30 to 682 nGy h^{-1}, which shows that the mean gamma doses in all but one (OGH) of these samples are higher than the world population-weighted average of 84 nGy h^{-1} indoor absorbed gamma dose rate.

The total effective dose A_{dTotal} ranged from 0.18 to 4.19 mSv y^{-1}. The estimated mean values of all but one (OGH) sample are higher than the world average value of 0.49 mSv y^{-1} for total effective dose, while all but OGE, OGG and OGH are higher than the recommended safe limit of 1 mSv y^{-1}. This is an indication that ionizing radiation doses that may be derived from external radiation from short-lived uranium and thorium progenies exceeded the internationally recommended annual effective dose threshold level for which intervention should be considered to reduce needless exposure of the public to ionizing radiation (Stegnar, Shishkov, Burkitbayev, Tolongutov, & Yunusov, 2013).

3.3. Radium equivalent activity concentration Ra_{eq}

Radium equivalent activity concentration (Ra_{eq}) is the quantity representative of external γ irradiation dose associated with a material. Ra_{eq} compares the specific activities of samples containing different concentrations of ^{238}U, ^{232}Th and ^{40}K. It is evaluated using equation (4) (Beretka & Matthew, 1985):

$$Ra_{eq} = C_U + 1.43C_{Th} + 0.077C_K \quad (4)$$

Where C_U, C_{Th} and C_K are the specific activity concentrations of ^{238}U, ^{232}Th, and ^{40}K in Bq kg^{-1} respectively. The results of the evaluated radium equivalent activity as presented in the seventh column of Table 2 varied from 33 to 871 Bq kg^{-1}. The calculated mean values are lower than the recommended safe limit of 370 Bq kg^{-1} (OECD, 1979), except for the sites OGA and OGD with values 421 and 546 Bq kg^{-1} respectively. This is an indication that quarry products from sites OGA and OGD may pose a significant radiological hazard when used as building construction material.

3.4. Activity concentration index (I)

This is another radiation hazard index primarily used to estimate the level of γ radiation associated with different concentrations of some specified radionuclides and can be expressed as follows

$$I = \frac{C_U}{A_U} + \frac{C_{Th}}{A_{Th}} + \frac{C_K}{A_K} \quad (5)$$

Where C_U, C_{Th}, C_K are the radium, thorium and potassium activity concentration in Bq kg^{-1} in the sample while A_U, A_{Th}, and A_K are the activity concentrations in Bq kg^{-1} of radium, thorium and potassium respectively that will produce a dose rate of 1 mSv y^{-1}.

Table 2 – Activity concentration, Hazard indexes (H_{in} and H_{ex}), Radium equivalent activity (Ra_{eq}) Absorbed dose rate (D_R), Annual effective dose (A_d) (indoor and outdoor) of the sampled quarry products. BDL ≡ below detection limit.

Sample ID	Activity concentration (Bq kg^{-1})			Hazard indices		Ra_{eq} (Bq kg^{-1})	D_R (nGyh^{-1})	Effective dose (mSv y^{-1})			I
	^{40}K	^{232}Th	^{238}U	H_{in}	H_{ex}			A_d outdoor	A_d indoor	A_d total	
OGA1	255 ± 4	561 ± 38	49 ± 1.26	2.48	2.36	871	682	0.84	3.35	4.19	3.05
OGA2	141 ± 3	111 ± 32	44 ± 1.17	0.70	0.58	214	175	0.21	0.86	1.07	0.75
OGA3	86 ± 3	92 ± 27	44 ± 1.16	0.61	0.49	182	148	0.18	0.73	0.91	0.63
OGA4	454 ± 5	164 ± 44	10 ± 0.55	0.78	0.76	279	226	0.28	1.11	1.39	1.00
OGA5	728 ± 6	317 ± 78	50 ± 1.25	1.64	1.51	559	452	0.56	2.22	2.78	1.99
Mean	**332**	**249**	**39**	**1.24**	**1.14**	**421**	**337**	**0.41**	**1.65**	**2.07**	**1.49**
OGB1	483 ± 5	52 ± 18	38 ± 1.04	0.51	0.41	150	131	0.16	0.64	0.81	0.55
OGB2	505 ± 5	129 ± 35	36 ± 1.01	0.80	0.70	260	216	0.27	1.06	1.33	0.94
OGB3	415 ± 4	65 ± 21	39 ± 1.05	0.55	0.44	163	140	0.17	0.69	0.86	0.59
OGB4	679 ± 6	143 ± 38	40 ± 1.07	0.91	0.80	297	248	0.30	1.22	1.52	1.07
OGB5	525 ± 5	46 ± 16	37 ± 1.02	0.49	0.39	143	127	0.16	0.62	0.78	0.53
Mean	**521**	**87**	**38**	**0.65**	**0.55**	**203**	**173**	**0.21**	**0.85**	**1.06**	**0.74**
OGC1	270 ± 4	188 ± 48	32 ± 0.93	0.96	0.87	322	259	0.32	1.27	1.59	1.14
OGC2	118 ± 2	74 ± 23	32 ± 0.97	0.48	0.40	147	120	0.15	0.59	0.74	0.52
OGC3	442 ± 5	160 ± 42	34 ± 0.98	0.89	0.80	297	243	0.30	1.19	1.49	1.06
OGC4	BDL	119 ± 31	30 ± 0.91	0.62	0.54	200	158	0.19	0.78	0.97	0.69
OGC5	637 ± 6	65 ± 19	23 ± 0.74	0.51	0.45	165	143	0.18	0.70	0.88	0.61
Mean	**293**	**121**	**30**	**0.69**	**0.61**	**226**	**185**	**0.23**	**0.91**	**1.13**	**0.80**
OGD1	1199 ± 8	216 ± 46	61 ± 1.26	1.42	1.25	463	391	0.48	1.92	2.40	1.69
OGD2	1271 ± 8	295 ± 60	61 ± 1.25	1.73	1.57	580	482	0.59	2.37	2.96	2.10
OGD3	2004 ± 12	253 ± 52	58 ± 1.21	1.70	1.55	574	491	0.60	2.41	3.02	2.12
OGD4	1615 ± 9	310 ± 63	56 ± 1.18	1.84	1.69	624	522	0.64	2.56	3.20	2.28
OGD5	1392 ± 10	231 ± 59	52 ± 1.33	1.47	1.33	490	414	0.51	2.03	2.54	1.80
Mean	**1496**	**261**	**58**	**1.63**	**1.48**	**546**	**460**	**0.56**	**2.26**	**2.82**	**2.00**
OGE1	158 ± 3	118 ± 32	23 ± 0.77	0.61	0.55	204	164	0.20	0.80	1.00	0.72
OGE2	542 ± 5	113 ± 31	44 ± 1.14	0.78	0.67	246	207	0.25	1.02	1.27	0.89
OGE3	562 ± 5	69 ± 21	15 ± 0.62	0.47	0.43	157	135	0.17	0.66	0.83	0.58
OGE4	100 ± 3	43 ± 15	32 ± 0.93	0.36	0.27	100	84	0.10	0.41	0.52	0.35
OGE5	1539 ± 11	18 ± 10	33 ± 0.96	0.57	0.48	178	174	0.21	0.85	1.07	0.72
Mean	**580**	**72**	**29**	**0.56**	**0.48**	**177**	**153**	**0.19**	**0.75**	**0.94**	**0.65**
OGF1	203 ± 3	142 ± 38	28 ± 0.83	0.74	0.67	247	198	0.24	0.97	1.22	0.87
OGF2	155 ± 3	182 ± 47	24 ± 0.77	0.87	0.80	297	235	0.29	1.15	1.44	1.04
OGF3	797 ± 7	120 ± 33	15 ± 0.64	0.71	0.67	248	210	0.26	1.03	1.29	0.92
OGF4	627 ± 5	154 ± 40	29 ± 0.89	0.88	0.81	298	247	0.30	1.21	1.51	1.08
OGF5	883 ± 8	94 ± 27	31 ± 0.91	0.71	0.63	234	202	0.25	0.99	1.24	0.87
Mean	**533**	**139**	**26**	**0.78**	**0.72**	**265**	**218**	**0.27**	**1.07**	**1.34**	**0.96**
OGG1	1158 ± 8	118 ± 27	42 ± 0.93	0.92	0.81	299	260	0.32	1.28	1.60	1.11
OGG2	954 ± 8	59 ± 20	33 ± 0.94	0.61	0.52	191	172	0.21	0.84	1.05	0.72
OGG3	55 ± 3	42 ± 16	26 ± 0.80	0.31	0.24	90	74	0.09	0.36	0.45	0.31
OGG4	959 ± 8	11 ± 8	5.35 ± 0.44	0.27	0.26	95	94	0.12	0.46	0.58	0.39
OGG5	571 ± 6	108 ± 30	31 ± 0.97	0.71	0.62	230	193	0.24	0.95	1.19	0.83
Mean	**740**	**67**	**27**	**0.56**	**0.49**	**181**	**159**	**0.19**	**0.78**	**0.97**	**0.67**
OGH1	49 ± 3	BDL	22 ± 0.75	0.15	0.09	33	30	0.04	0.15	0.18	0.12
OGH2	57 ± 3	41 ± 12	30 ± 0.77	0.33	0.25	93	77	0.09	0.38	0.47	0.32
OGH3	49 ± 3	57 ± 15	26 ± 0.71	0.37	0.30	110	90	0.11	0.44	0.55	0.38
OGH4	91 ± 3	58 ± 16	26 ± 0.72	0.38	0.31	116	95	0.12	0.47	0.58	0.41
OGH5	213 ± 3	60 ± 16	28 ± 0.75	0.43	0.35	131	109	0.13	0.54	0.67	0.47
Mean	**92**	**44**	**26**	**0.33**	**0.26**	**97**	**80**	**0.10**	**0.39**	**0.49**	**0.34**
OGI1	886 ± 8	74 ± 22	37 ± 1.07	0.67	0.57	212	187	0.23	0.92	1.15	0.79
OGI2	1008 ± 8	167 ± 45	46 ± 1.19	1.10	0.98	362	307	0.38	1.50	1.88	1.32
OGI3	1590 ± 11	119 ± 34	43 ± 1.14	1.02	0.91	336	298	0.37	1.46	1.83	1.27
OGI4	1069 ± 9	177 ± 47	44 ± 1.16	1.14	1.03	379	320	0.39	1.57	1.97	1.39
OGI5	866 ± 7	82 ± 25	43 ± 1.13	0.73	0.61	227	199	0.24	0.98	1.22	0.84
Mean	**1084**	**124**	**43**	**0.93**	**0.82**	**303**	**262**	**0.32**	**1.29**	**1.61**	**1.12**
OGJ1	179 ± 3	71 ± 10	71 ± 1.13	0.70	0.51	187	158	0.19	0.78	0.97	0.65
OGJ2	321 ± 4	21 ± 10	53 ± 1.14	0.43	0.29	108	97	0.12	0.48	0.60	0.39
OGJ3	322 ± 4	62 ± 17	61 ± 1.24	0.64	0.47	174	150	0.18	0.74	0.92	0.62
OGJ4	700 ± 6	136 ± 37	49 ± 1.25	0.94	0.80	297	251	0.31	1.23	1.54	1.08
OGJ5	443 ± 5	85 ± 25	48 ± 1.24	0.68	0.55	203	173	0.21	0.85	1.06	0.73
Mean	**393**	**75**	**57**	**0.68**	**0.52**	**194**	**166**	**0.20**	**0.81**	**1.02**	**0.69**
Column average	**719.90**	**147.26**	**43.65**	**0.95**	**0.84**	**310**	**260**	**0.32**	**1.28**	**1.59**	**1.12**

In order to examine whether a building material meet the annual effective dose criteria of 1 mSv for materials used in bulk amount, gamma activity concentration index (I) was derived with a value of 300, 200 and 3000 Bq kg^{-1} for A_U, A_{Th}, and A_K respectively (EC, 1999):

$$I = \frac{C_U}{300Bq/kg} + \frac{C_{Th}}{200Bq/kg} + \frac{C_k}{3000Bq/kg} \quad 6$$

For materials used in bulk amount, such as studied in this work, the exception dose criterion of 1 mSv y^{-1} correspond to an activity concentration index $I \leq 1$. The result of activity concentration index is presented in column twelve of Table 2. A good number of these samples have $I > 1$, supporting the fact that granites from some of these sites exhibit high gamma radiation level.

3.5. *External radiation index (H_{ex})*

In order to evaluate the external gamma radiation emanating from building materials, the external hazard index H_{ex} was calculated by the following equation (Beretka & Matthew, 1985):

$$H_{ex} = \frac{C_U}{370\ Bq/kg} + \frac{C_{Th}}{258\ Bq/kg} + \frac{C_K}{4810\ Bq/kg} \leq 1 \quad 7$$

Where C_U, C_{Th} and C_K are the specific activity concentrations of ^{238}U, ^{232}Th, and ^{40}K in Bq kg^{-1} respectively. To ensure the safe use of these samples as a building material and to keep the radiation hazard insignificant, the value of H_{ex} should be less than unity (Rati et al., 2010). As shown in column 6 of Table 2, the mean values of H_{ex} for OGA and OGD were higher than the recommended safe limit while the mean H_{ex} for the remaining groups were less than unity indicating that their radiation hazard is insignificant and are safe to be used as a building material.

3.6. *Internal radiation hazard index (H_{in})*

The internal hazard index (H_{in}) gives the internal exposure to carcinogenic radon and its short-lived progeny. The value of H_{in} must also be less than unity to have negligible hazardous effects of radon and its short-lived progeny to the respiratory organs (Ramasamy, Paramasivan, Suresh, & Jose, 2014).

$$H_{in} = \frac{C_U}{185\ Bq/kg} + \frac{C_{Th}}{259\ Bq/kg} + \frac{C_K}{4810\ Bq/kg} \leq 1 \quad 8$$

Where C_U, C_{Th} and C_K are the specific activity concentrations of ^{238}U, ^{232}Th, and ^{40}K in Bq kg^{-1} respectively. The calculated H_{in} values ranged from 0.15 to 2.48 as shown in Table 2.

4. Statistical analysis

4.1. *Principal component analysis*

Principal component (PCA) analysis is useful for reducing and interpreting large multivariate data sets with underlying linear structures, and for discovering previously unsuspected relationships. The principal component Analysis yields a two component representation of the acquired data, in which 93.3% of the total variance was explained. The principal components of the variables are shown in Table 3.

4.2. *Pearson correlation analysis*

Pearson correlation analysis was carried out on all the evaluated variables to determine the mutual relations and the degree of association between pairs of variables. Table 4 shows the Correlation coefficient Matrix of all the radiological variables for the quarry products of southwest Nigeria. It can be seen from the table that a high positive correlation exist among all the variables as all values are greater than 0.3.

4.3. *Loading plot*

The Loading plot reveals the relationships between variables in the space of the first two components. In the loading plot, Fig. 1, we can see that ^{238}U and ^{40}K have similar heavy loadings for principal component 2. However, the gamma absorbed dose rate (D_R), radium equivalent activity (Ra_{eq}), annual effective dose (A_d), activity concentration index (I), external radiation hazard index (H_{ex}), internal radiation hazard index (H_{in}), have similar heavy loadings for principal component 1.

5. Conclusion

The activity concentration, gamma absorbed dose rate, radium equivalent activity, annual effective dose and various radiological hazard indices of quarry products from southwest Nigeria have been analysed using gamma spectrometry technique. The extracted values are, in general, comparable to the average worldwide ranges. A few of the measured radiological parameters are higher than permissible limit. Hence harmful radiation effects may be posed to the public as a result of the natural radioactivity of quarry products when such samples with enhanced radioactivity are used as a building construction material. This study can be used as a baseline for future research work and the data obtained in this study may be useful for natural radioactivity mapping and

Table 3 – Principal components of the variables.

Variables	Principal components	
	1	2
^{40}K	0.199	0.725
^{232}Th	0.323	0.725
^{238}U	0.194	0.559
H_{in}	0.342	−0.049
H_{ex}	0.341	−0.100
Ra_{eq}	0.341	−0.099
D_R	0.342	−0.029
A_d (outdoor)	0.342	−0.029
A_d (indoor)	0.342	−0.029
I	0.342	−0.059

Table 4 – Pearson correlation matrix.

Variables	^{40}K	^{232}Th	^{238}U	H_{in}	H_{ex}	Ra_{eq}	D_R	A_d (outdoor)	A_d (indoor)	I
^{40}K	1									
^{232}Th	0.30548	1								
^{238}U	0.34267	0.40061	1							
H_{in}	0.52964	0.95748	0.57029	1						
H_{ex}	0.52415	0.9678	0.51056	0.99748	1					
Ra_{eq}	0.52482	0.9676	0.51081	0.9975	1	1				
D_R	0.5807	0.94822	0.52717	0.9966	0.9976	0.99765	1			
A_d outdoor	0.58071	0.94822	0.52717	0.9966	0.9976	0.99765	1	1		
A_d indoor	0.5807	0.94822	0.52717	0.9966	0.9976	0.99765	1	1	1	
I	0.56291	0.95609	0.51141	0.99656	0.99893	0.99896	0.99962	0.99962	0.99962	1

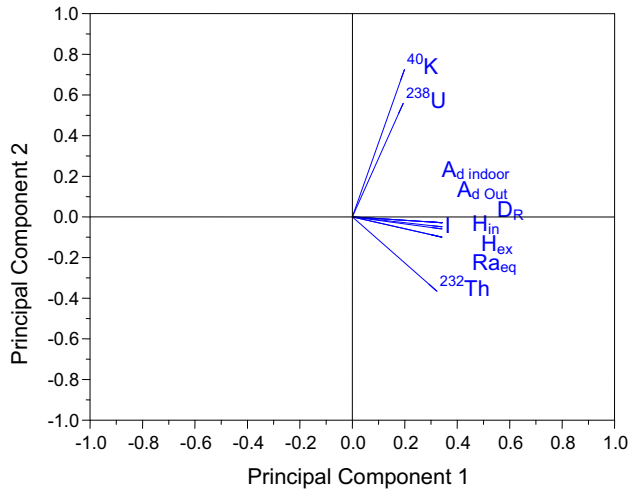

Fig. 1 – Loading plot of the variables.

also be used as a reference data for monitoring possible radioactivity pollution in the future.

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